Development of electric heating actuators of fiber reinforced metal composite

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Two types of electric heating actuators used of SiC_{CVD} fiber reinforced aluminum composite were successfully developed, which could be used at elevated temperature. The experimental results reveal that the temperature of the actuators increases with the increase of the given electric power. The maximum temperature was found to be higher the 150 and 200°C for 1-side electric heating actuator and 2-side electric heating actuator, respectively, when the electric power of about 10 W were given. It is found that the electric resistance of the actuators decreases obviously with the increase of temperature. A critical temperature was found to exist for the change of the displacement and curvature. The displacement and curvature almost remained unchanged when the temperature of the actuators was lower than the critical temperature. After that, the displacement and curvature increase with the rise of the actuator temperature. Because the 1-side and 2-side actuators have different response characteristics of the displacement and generated force, it is expected that the two types of actuators may be used in different areas.

1. Introduction

The SiC/Al composites have been widely investigated as an excellent structural material due to their high specific strength and specific modulus [1–5]. In these investigations, some work was focused on the aluminum matrix composites reinforced by the SiC_{CVD} fibers. The authors have examined the strength reliability of composite relating to the fiber volume fraction [6], the interfacial shear strength [7], residual stress [8] and the size effect. The SiC_{CVD} continuous fiber has used a carbon core with 30 μm diameter and a carbon coating layer of about 1 μm thickness on the outside surface. Because the SiC and carbon fibers do not only have good mechanical properties as the reinforcement, but also have many excellent functional properties as semiconductors and electric heaters [9], the investigation on the functional properties of the SiC and carbon fibers has attracted an increasing interest in the past five years. The authors have used SiC_{CVD} fiber to investigate strength reliability of single fiber and fiber bundle of ceramics [10, 11]. It is clarified that the SiC_{CVD} fiber is used as excellent electric heater using the behavior of electric resistant at room and high temperatures [12]. Besides, developing actuation function of composite to reduce vibration and noise, and to control shape and self-repair of material is greatly noticed recently [13]. In 1999, CFRP/KFRP/metal actuator and active composite devices using electric heating of carbon fiber were developed [14, 15]. In that work, it is interesting that the mechanism is simple, to apply asymmetry of thermal expansion in the cross-section of the composite. However, application of the electric heating actuators with plastic matrix is limited to lower temperature. An all-organic composite actuator material with a high dielectric constant was developed in 2002 to expect applying human muscle [16]. Composites of metal and plastics matrix with heat-response, which use shape active alloy, were also developed [17, 18]. Furthermore, the application of composite actuators to control robot [19] and roll maneuver of airplane wing [20] was tried in 2002.

In the present investigation, a new idea to develop actuator of metal matrix composite was suggested, and the SiC_{CVD} fibers in SiC_{CVD} fiber reinforced aluminum composite were used as the reinforcement as well as electric heater. Two types of electric heating actuators using SiC_{CVD} fiber reinforced aluminum composite fabricated by hot press method were developed, which could be used at elevated temperature. The response characteristics of temperature, curvature and generated force during electric heating were investigated and discussed.

2. Experimental

2.1. Fabrication of the composite

An A1050 pure aluminum plate with thickness of 0.2 and 0.4 mm was used as the matrix material. The

TABLE I Properties of SiC_{CVD} fiber, pure Al, Carbon fiber and SiC fiber

Materials	Density (g/cm^3)	Young's modulus (GPa)	Electric resistivity ($\Omega \cdot$cm)	CTE ($\times 10^{-6}$/K)	Heat capacity (J/g $\cdot$ K)
SiC_{CVD} fiber	3.05	421.7	1.9×10^1	1.5	–
Pure Al	2.7	68.6	2.8×10^{-12}	23.6	0.9
Carbon fiber	1.77	240	$0.8–1.5 \times 10^{-3}$	−0.7	0.71
SiC fiber	2.55	220	$10^3–10^4$	2.2	1.14

Carbon fiber: TOHO RAYON CO., LTD.
SiC fiber: NIPPON Carbon CO., LTD.
SiC_{CVD} fiber: SCS-2, Textron Specialty Materials CO., LTD.
Pure Al: 1050P.

SiC_{CVD} fiber (type: SCS-2, diameter: 140 μm) was used as both the reinforcement and the electric heater. Density, Young's modulus, electric resistivity, CTE and heat capacity of the SiC_{CVD} fiber and the pure aluminum used in present investigation are listed in Table I. For reference, the parameters of carbon fiber and SiC fiber were also listed in Table I. It can be seen that electric resistivity of the SiC_{CVD} fiber is between carbon fiber and SiC fiber, and the CTE of SiC_{CVD} fiber is as small as about 15 times of pure aluminum. SiC_{CVD}/Al composite was fabricated using following procedure. Firstly, the aluminum plate was cut into pieces of 30×70 mm^2, which were then annealed at 573 K for 30 min in air. In order to arrange the fibers on the aluminum pieces orderly, U-shaped grooves with inter-space of 0.5 mm were made on one side of the aluminum pieces with thickness of 0.2 mm by pressing the stainless steel wires with diameter of 140 μm into the pieces. After that, the SiC_{CVD} fibers were cut into a length of 70 mm from the obtained continuous SiC_{CVD} fiber, and then were put into the grooves on the surface of each aluminum piece. After putting the SiC_{CVD} fibers into the grooves, the aluminum piece was then overlapped by another aluminum piece with a thickness of 0.4 mm. To deviate the fibers from the center of the cross-section of the composite, aluminum pieces with different thickness were used in the present work. Finally, this one-layer SiC_{CVD}/Al preform was hot pressed into the composite under the pressure of 56 MPa for 40 min at 893 K in the atmosphere. The SiC_{CVD}/Al composite fabricated by this way has the thickness of about 0.5 mm, fiber volume fraction of 9.2% and the fiber spacing of about 0.25 mm.

2.2. Fabrication of the actuators

The SiC_{CVD}/Al composite was cut into 10×70 mm^2 pieces along the fiber direction, and each piece contains 30 SiC_{CVD} fibers. Then the pieces of the composite were annealed at 573 K for 10 min. The aluminum matrix of the one side or the two sides was corroded and dissolved with 5%NaOH water solution, and the exposed SiC_{CVD} fibers were used as the electrodes for electric heating. An outward view of the composite pieces for the two types of actuators is given in Fig. 1. The schematic diagrams and dimensions of the actuators are given in Fig. 2. In the case of exposing the one side, 4 SiC_{CVD} fibers, which were located at the center of exposed 30 SiC_{CVD} fibers, were cut off, and the each remaining 13-SiC_{CVD} fibers were wrapped with copper foil of 4 mm width as the two electrodes, respectively. In the case of exposing the two sides, the each 30-SiC_{CVD} fibers on the two sides were wrapped with copper foil of 4 mm width as the two electrodes, respectively. The two types of actuators obtained from the above mentioned were named as 1-side and 2-side electric heating actuator, respectively. A SEM image of cross section microstructure of the actuator is shown in Fig. 3. It can be seen that

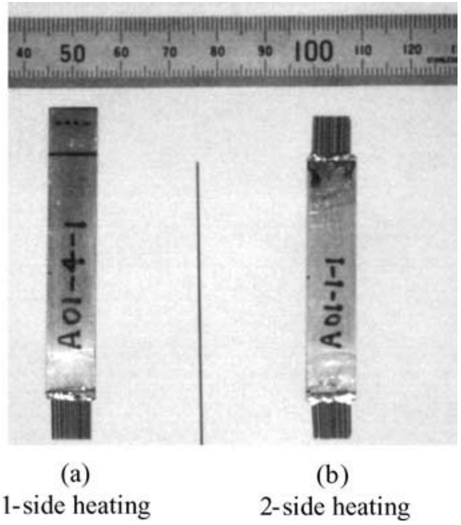

Figure 1 Photocopy of SiC_{CVD}/Al composite actuators.

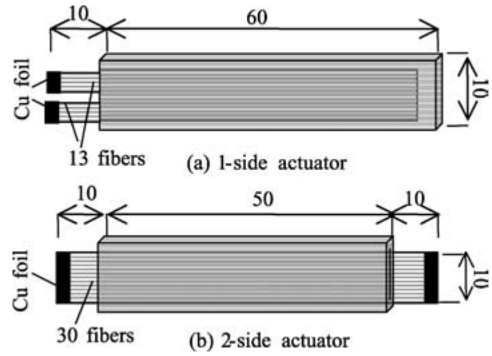

Figure 2 Schematic diagrams and dimensions of SiC_{CVD}/Al composite actuators.

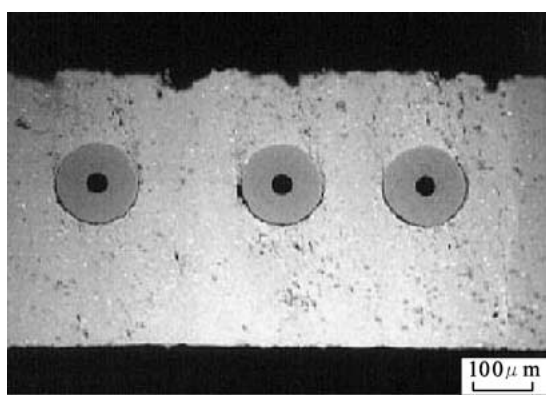

Figure 3 SEM micrograph of cross section of SiC_{CVD}/Al composite actuator.

the composite with deviating the fibers from the center of the cross-section, that is, with an asymmetry of thermal expansion along the direction of the thickness and having a good compound between the finer and the matrix is obtained.

2.3. Measurement of the response characteristics

A schematic drawing for measuring the response characteristics of the 1-side electric heating actuator is given in Fig. 4. The one side of the actuator was fixed, and electric power was impressed into the two electrodes by the same side. The displacement and generated force were measured by a ruler and a spring balancer at the other side, respectively. The temperature in the actuator was measured at three points (I, II and III) (Fig. 4), and the average value of three points was used in some cases. A schematic drawing for measuring the response characteristics of the 2-side electric heating actuator is given in Fig. 5. The two sides of the actuator were fixed, and electric power was impressed into the two electrodes through the two sides. Actuator temperature was also measured at three points (I, II and III), but the displacement and generated force were measured at the center. A direct-current power source was used for heating the actuators. The displacement and the distance between the fixing end and displacement measurement point were expressed by x and y, respectively, and the actuator curvature can be calculated by

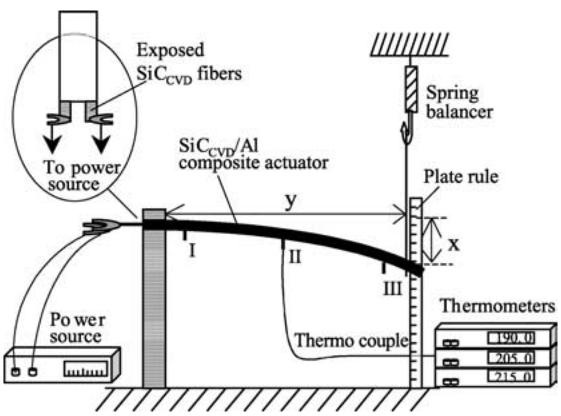

Figure 4 Schematic diagram of the measuring system of temperature, displacement and generated force for the 1-side heating actuator.

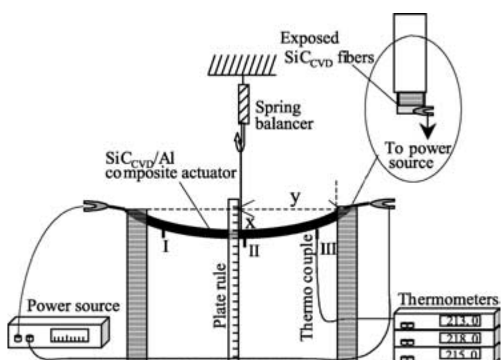

Figure 5 Schematic diagram of the measuring system of temperature, displacement and generated force for the 2-side heating actuator.

Equation 1

$$r^{-1} = 2x/(x^2 + y^2) \tag{1}$$

3. Results and discussion

3.1. Electric resistant and heating temperature of the actuators

Though the electric resistance of the actuator is related to length of the exposed fibers and width of the wrapped copper foil, the electric resistance of the actuators is very small, 25 and 15 Ohm at room temperature for the 1-side and 2-side electric heating actuators, respectively. Relationship between the electric resistance and the temperature of the actuators during electric heating is shown in Fig. 6. It can be seen that the electric resistance of the actuators decreases with the increase of temperature for the two types of actuators, which can

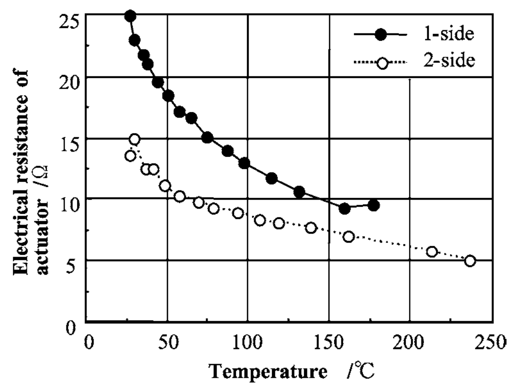

Figure 6 Relationship between temperature and electric resistance of SiC_{CVD}/Al composite actuator.

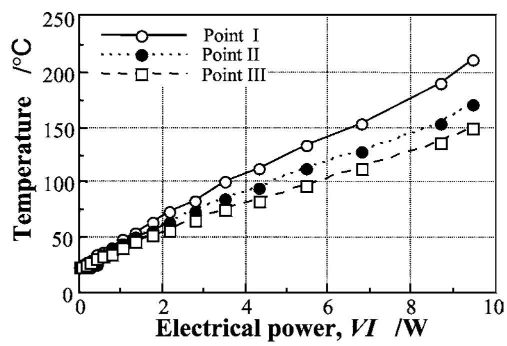

Figure 7 Relationship between electrical power and temperature of 1-side heating actuator.

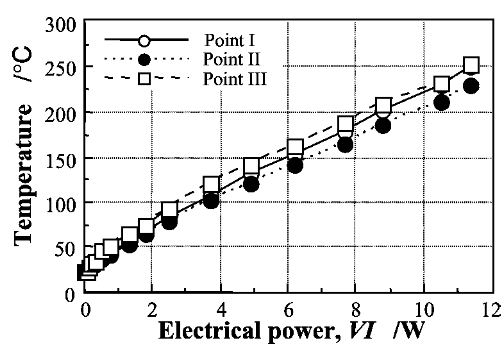

Figure 8 Relationship between electrical power and temperature of 2-side heating actuator.

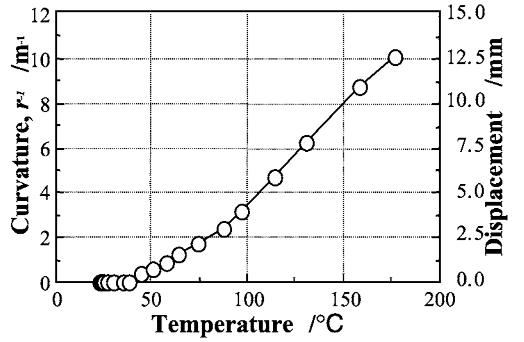

Figure 9 Relationship between temperature and curvature of 1-side heating actuator.

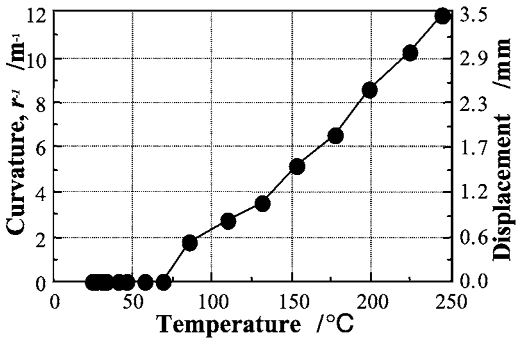

Figure 10 Relationship between temperature and curvature of 2-side heating actuator.

be explained by author's previous results [12]. In the previous work, electrical resistance of the SiC_{CVD} fiber was measured from room temperature to 1000°C. It was found that the electrical resistance decreases with the increase of temperature until 1000°C. As known, electric resistance of aluminum metal used as the matrix increases with increase of temperature. Therefore, it is considered that the electric resistance of the actuator is mainly influenced by the SiC_{CVD} fibers.

Relationship between the given electric power and the temperatures of the 1-side and 2-side electric heating actuators is given in Figs 7 and 8. The differences between temperature from point I to III of 1-side actuator, and between temperatures of 1-side and 2-side actuators as shown in Figs 7 and 8 are related to the structures factors such as numbers of SiC_{CVD} fibers used as heating element and the exposed SiC_{CVD} fibers at 1 side or 2 sides and so on. The effects of the electric power on the temperature of the actuators were found to show almost same patterns for two types of actuators. That is, the temperature of the actuators increases with the increase of the given electric power. The maximum temperature was found to be higher the 150 and 200°C for 1-side actuator and 2-side actuator, respectively, when the electric power of about 10 W were given.

3.2. Temperature and curvature of the actuators

The temperature, displacement and the curvature of the two types of actuators are given in Figs 9 and 10. A critical temperature was found to exist for the change of the displacement and curvature. The critical temperature was about 40 and 70°C for the 1-side and 2-side electric heating actuator, respectively. The displacement and curvature almost remained unchanged when the temperature of the actuators was lower than the critical temperature. After that, the displacement and curvature increase quickly with the increase of temperature. Comparing the displacement of the two

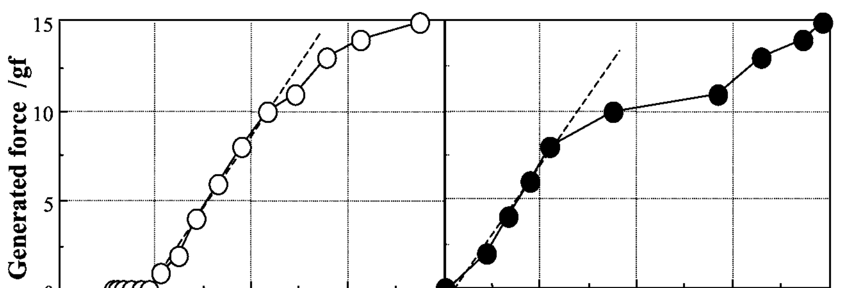

Figure 11 Relationship between temperature, curvature and force of 1-side heating actuator.

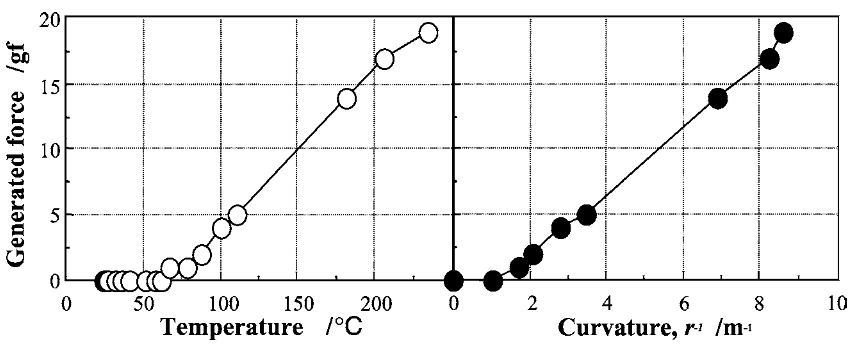

Figure 12 Relationship between temperature, curvature and force of 2-side heating actuator.

types of actuators, the maximum displacement of the 1-side electric heating actuator was bigger than 12.5 mm, which was 3.5 times of that in the 2-side electric heating actuator.

3.3. Temperature and generated force of the actuators

Relationship between the generated force and the temperature or the curvature for two types of actuators is given in Figs 11 and 12. The generated force also rises with the increase of temperature or the curvature for the two types of actuators. The generated force in the 2-side actuator was found to reach about 20 gf, which was bigger than that in the 1-side electric heating actuator. This may be because that 2-side electric heating actuator is supported by the two sides.

4. Conclusion

Two types of the electric heating actuators using one-layer unidirectional SiC_{CVD}/Al composite were suggested and successfully developed. The developed actuators can be heated well by electric power. The big response characteristics such as the displacement, curvature and generated force can be obtained with the change of the temperature in the actuator. Because the 1-side and 2-side electric heating actuators have different response characteristics of the displacement and generated force, it is expected that the two types of actuators may be used in different indifferent fields.

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